

# Phosphorus fractions and phosphomonoesterase activities in sandy soils under a temperate savanna and a neighboring Mongolian pine plantation

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**Abstract:** To assess the effects of savanna afforestation on soil phosphorus (P) transformations in eastern Horqin Sandy Land, China, P fractions and phosphomonoesterase activities were examined in two soil horizons (0–5 cm and 5–20 cm) under a savanna and an adjacent 30-year-old Mongolian pine (*Pinus sylvestris* L. var. *mongolica* Litv.) plantation on a P-deficient semi-arid sandy soil. The results showed that all soil P fractions and phosphomonoesterase activities decreased with soil depth at both sites except that labile organic P under the plantation was constant with soil depth. In contrast to savanna, soils under Mongolian pine plantation had lower phosphomonoesterase activities and concentrations of all P fractions (with an exception of Al-P), lower proportions of organic P and Ca-P in total P, and higher proportions of labile P, Al-P and Fe-P in total P. These results suggested that P transformations mainly occurred in surface soils, and P recycled through litter-fall was the most important source of plant available P. Mongolian pine afforestation enhanced the bioavailability of both organic P and Ca-P, simultaneously reduced soil P pools, indicating that protection of forest floor and P fertilization are necessary to maintain the sustainable functioning of Mongolian pine plantations.

**Keywords:** Afforestation; P fractions; P bioavailability; Phosphomonoesterase activity; Sandy soil

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## Introduction

Compared with other major nutrients, phosphorus (P) is unrenewable and by far the least available to plants in most soil conditions. Phosphate ions in the soil solution which takes part in the biological cycle are only a little proportion (often 0.1–10 µM) of soil total P. Additionally, the movement of phosphate ions through the soil to the root surface occurs by diffusion (Smith 2002) which is particularly sensitive to soil moisture regimes. Therefore, P is frequently a major limiting factor for plant growth. P transformations within and between ecosystem components, such as soil sub-system, play a central role in maintaining ecosystem structure and function, especially in arid regions (e.g., Ae *et al.* 1990; Hinsinger 2001; Kellogg *et al.* 2003). Bioavailable P in the soil was controlled by mineralization–immobilization of organic P, adsorption–desorption and precipitation–dissolution of inorganic P (Frossard *et al.* 2000), which was influenced by the actions and interactions of vegetation type, edaphic character, environmental condition and land management practice (e.g., Lajtha *et al.* 1988; Leinweber *et al.* 1999; Chen *et al.* 2003).

Both soil organic and inorganic P consist of P compounds of different bioavailability. Different forms of P compounds exist in equilibrium with each other through transformation processes. Inorganic phosphate ions is easily adsorbed and precipitated in

the soil by oxides of Fe, Al and CaCO<sub>3</sub> (Parfitt 1978). Usually, organic P (20% to 90% of total P) dominates over soil P in forest soils. Mineralization of organic P is deeply mediated by microbial activities and phosphatase enzymes (Magid *et al.* 1996; Frossard *et al.* 2000). Phosphatases are inducible enzymes excreted by plant roots and soil organisms, which can be stimulated by P starvation. Therefore, phosphatase activities have been regarded as an important factor in maintaining and controlling mineralization rate soil organic P, and a good indicator of P deficiency (Baldwin *et al.* 2001; Vance *et al.* 2003).

Effects of grassland afforestation on soil chemical properties have been widely studied. Most studies showed that afforestation on grassland (planted with *Pinus radiata*, *P. ponderosa*, *P. nigra*) resulted in an overall reduction of soil quality, such as increases in soil acidity and P bioavailability, enhancement in mineralization of soil organic P, reductions of organic C, total N and P, and soil biological activities (Alfredsson *et al.* 1998; Condon *et al.* 1996; Chen *et al.* 2000; Chen *et al.* 2003). Other studies showed that planted *P. radiata* forests had no influence on soil total P and available P (Farley *et al.* 2004). The reason for the different results may depend on edaphic and climate characters of studied region. It is worthy to note that all above studies on the absolute concentration of soil P fractions in humid regions did not consider the distribution of soil P in different forms. Proportions of soil P in different forms can better reflect the relative contribution of specific P fraction to soil P transformations. Additionally, studies on responses of soil P to afforestation on semi-arid savanna have been poorly documented.

Mongolian pine (*P. sylvestris* L. var. *mongolica* Litv.) is an ecologically important coniferous tree species in northern China. Due to its good performance in early growth stage, since the 1960s it has been largely planted for stabilizing sand dunes and for preventing water erosion and desertification in Three-North Region of China (Zeng *et al.* 1996). Just in eastern Horqin Sand Land, planting area has reached 35 000 hm<sup>2</sup> and accounts for over 20% of all forested land in the region. This unprecedented

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rate of afforestation has resulted in changes in ecological processes in soils, which affects soil stability and fertility. In a previous study we reported the patterns of N cycling under Mongolian pine plantations in the region (Chen *et al.* 2005). However, no quantitative information exists on the impact of land-use changes on the amount and structural composition of P in this region. A better understanding of P cycling and its response to land-use change in arid regions will facilitate the management of arid ecosystems in a sustainable manner. Objective of this study is to assess the influences of pine afforestation on P transformations in the semi-arid sandy soil, by comparison of soil P fractions, PA and related soil properties between native savanna and Mongolian pine plantation.

## Materials and methods

### Site description and soil sampling

The study sites were located in Daqinggou National Reserve in Inner Mongolia, China (42°45'–42°48'N, 122°13'–122°15'E, and 225–253 m above mean sea level), belonging to a temperate semiarid climate zone. Annual rainfall is about 450 mm, with

more than 70% occurring from June to August. Annual temperature is about 6 °C (highest is 29 °C in June, lowest is –30 °C in January). There is a long winter period, often from November to next March. The soil is a type of poor sandy soil weakly developed from windblown sand. Selected soil properties are summarized in Table 1.

Temperate savanna is one of common native vegetations in this area. This savanna consists of dense grasses (dominantly *Artemisia scoparia*, *Erodium stephanianum* and *Phragmites australis*), sparse *Ulmus pumila* trees and shrubs of *Lespedeza bicolor*, *Prunus armeniaca* and *Crataegus pinnatifida*.

Mongolian pine, native in Hulunbeier Sand Lands (47°10'–49°08'N, 118°21'–122°45'E) and on the bottom of west slope of Greater Xing'an Mountains (49°46'–53°35'N, 119°50'–127°29'E), has a high adaptation to aridity, cold and infertility and characteristically has a short growing period in tree height during spring usually from late April to early June in present study area. Dominant understory species in Mongolian pine plantations include *Setaria viridis*, *Leonurus sibiricus*, *Lespedeza bicolor* and *Lxeris sonchifolia*.

**Table 1.** Soil properties in Mongolian pine plantation and savanna\*

Vegetation	Depth (cm)	Soil moisture (%)	pH	Bulk density (g·cm <sup>-3</sup> )	Soil organic C (mg·g <sup>-1</sup> )	Total N (mg·g <sup>-1</sup> )	Total K (mg·g <sup>-1</sup> )
Pine plantation	0–5	2.1±0.4 <sup>b</sup>	6.56±0.07 <sup>b</sup>	1.44±0.02 <sup>a</sup>	8.3±0.7 <sup>b</sup>	0.63±0.06 <sup>b</sup>	23.3±1.8 <sup>a</sup>
	5–20	2.8±0.2 <sup>b</sup>	6.56±0.02 <sup>b</sup>	1.48±0.02 <sup>a</sup>	4.1±0.2 <sup>b</sup>	0.37±0.02 <sup>b</sup>	23.9±1.5 <sup>a</sup>
Savanna	0–5	2.2±0.7 <sup>b</sup>	6.85±0.10 <sup>a</sup>	1.47±0.05 <sup>a</sup>	29.9±4.0 <sup>a</sup>	1.61±0.2 <sup>a</sup>	25.1±1.4 <sup>a</sup>
	5–20	4.5±0.3 <sup>a</sup>	6.89±0.09 <sup>a</sup>	1.51±0.04 <sup>a</sup>	8.9±0.6 <sup>b</sup>	0.69±0.1 <sup>b</sup>	25.6±1.7 <sup>a</sup>

**Notes:** \* Data are means ( $n = 5$ ) ± SE. Values within columns with different superscript letters were significantly different at  $P < 0.05$  (LSD following ANOVA).

An undisturbed 30-year-old Mongolian pine plantation (3 m × 2 m spacing) that was established on former savanna after site preparation and an adjacent savanna were selected as study sites. Five plots were selected at each site for soil sampling. Soil samples were collected on April 20, 2004 when Mongolian pine trees began fast growing. Soil was collected from two depths: 0–5 cm and 5–20 cm. The reason is that no obvious horizons were observed in soil profile, and most Mongolian pine roots present at 5–20 cm depth or deeper, whereas roots of grasses in both savanna and under the plantation mainly present at 0–10 cm depth. 15 soil cores were sampled randomly per horizon per plot (using an auger with inner diameter of 6 cm) and were composited into one soil sample. Soil samples in the pine plantation were collected along the tree rows (50 cm from tree boles). Each soil sample was screened through a 2-mm sieve, and divided into three subsamples: One was stored at 4°C before the measurements of microbial biomass P (MBP) and phosphomonoesterase activities (PA); The second one was air-dried for the chemical analyses of soil pH, labile inorganic P (LP<sub>i</sub>), total labile P (LP<sub>t</sub>) and labile organic P (LP<sub>o</sub>); The third one was air-dried and ground to screen through a 0.14-mm sieve for the chemical analyses of soil organic carbon, total nitrogen, total P (TP), total organic P (TP<sub>o</sub>), and fractionations of inorganic P.

### Soil analyses

Soil pH was measured at a soil: water ratio of 1: 2.5. Gravimetric soil moisture was calculated from mass loss after drying for 48 h at 105°C. Soil organic carbon concentration was determined by the Walkey-Black method (Nelson *et al.* 1982). Total N concentration was determined by steam distillation after Kjeldahl

digestion at 370°C. Total potassium (K) concentration was tested by flame photometry after H<sub>2</sub>SO<sub>4</sub>-HClO<sub>4</sub> digestion.

TP concentration was determined following H<sub>2</sub>SO<sub>4</sub>-HClO<sub>4</sub> digestion (Olsen *et al.* 1982). TP<sub>o</sub> concentration was measured by a modified Saunders and Williams (1955) ignition procedure. Ignited and unignited soils were extracted for 1 h with 1-mol·L<sup>-1</sup> H<sub>2</sub>SO<sub>4</sub>. TP<sub>o</sub> was calculated as the difference between phosphates in the ignited and unignited samples. Total inorganic P (TP<sub>i</sub>) concentration was the difference between TP and TP<sub>o</sub>.

Soil MBP concentration was analyzed by fumigating soil samples with chloroform for 24 h before extracting soil with 0.5-mol·L<sup>-1</sup> sodium bicarbonate (NaHCO<sub>3</sub>, pH 8.5), and employing an efficiency factor ( $K_p$ ) of 0.4 (Brookes 1982). PA was determined by the method of Tabatabai (1994) at pH 6.5. Enzyme activities were expressed as  $\mu\text{g}\cdot\text{g}^{-1}\cdot\text{h}^{-1}$  ( $p\text{-NP}$  = para-nitrophenol). LP<sub>i</sub> and LP<sub>o</sub> concentrations (0.5-mol·L<sup>-1</sup> NaHCO<sub>3</sub> extracted inorganic and organic P) were measured by the Bowman and Cole (1978) method. Concentrations of inorganic P fractions were determined by a modified Chang and Jackson procedure (Petersen *et al.* 1966), soil samples were sequentially extracted with 0.5-mol·L<sup>-1</sup> NH<sub>4</sub>F for Al-P (aluminum bound P), 0.1-mol·L<sup>-1</sup> NaOH for Fe-P (iron bound P), 0.5-mol·L<sup>-1</sup> H<sub>2</sub>SO<sub>4</sub> for Ca-P (calcium bound P). All the phosphates were measured by molybdenum blue method. In order to study the distribution of soil P in different forms, amounts of soil P fractions were expressed as both the absolute concentrations and the percentages in total P.

### Statistical analyses

Analyses of variance (ANOVA) were used to test the signifi-

cance of the effects of vegetation type and soil depth on soil P properties. The least significant difference (LSD) test was used to separate the means when difference was significant ( $P < 0.05$ ). Above processes were calculated with SPSS 11.5 software.

## Results

### Total P and total inorganic, organic P

Concentration of TP ranged between 67.5 and 244.4  $\mu\text{g}\cdot\text{g}^{-1}$  across studied sites. Concentrations of TP,  $\text{TP}_i$  and  $\text{TP}_o$  decreased with soil depth at both sites (Table 2). TP and  $\text{TP}_o$  were significantly higher under savanna than those under pine plantation, but  $\text{TP}_i$  had no difference between two sites (Table 2). Average TP and  $\text{TP}_o$  in two soil horizons under savanna were about 2.35, and 3.54 times of those under pine plantation. Vegetation type influ-

enced not only concentrations of soil P, but also their vertical distribution within soil profile. Differences between surface soils and subsoils in TP and  $\text{TP}_o$  under savanna were significantly greater than those under pine plantation. Also, concentration of  $\text{TP}_o$  in surface soils was more easily subjected to vegetation change than that in subsoils. Averaged across both soil horizons, the ratio of  $\text{TP}_o$  to TP under pine plantation (43.5%) was significantly lower than that under savanna (66.2%). Soil depth did not influence the ratio of  $\text{TP}_o$  to TP at both sites.

The ratio of soil organic carbon to organic phosphorus (C:  $\text{TP}_o$ ) ranged between 102.8 and 210.8 (Table 3). It decreased with soil depth at both sites, and was higher under pine plantation than under savanna in both soil horizons. Additionally, Influence of vegetation type on it was more obvious in subsoils.

**Table 2. Concentrations of soil P fractions ( $\mu\text{g}\cdot\text{g}^{-1}$ ) and phosphomonoesterase activities**

Vegetation	Depth (cm)	TP	TP <sub>i</sub>	TP <sub>o</sub>	LP <sub>t</sub>	LP <sub>i</sub>	LP <sub>o</sub>	Al-P	Fe-P	Ca-P	MBP	PA
Pine plantation	0–5	109.8±4.1 <sup>c</sup>	64.8±2.8 <sup>ab</sup>	45.1±3.1 <sup>d</sup>	4.7±0.5 <sup>b</sup>	1.7±0.4 <sup>b</sup>	3.0±0.6 <sup>b</sup>	6.6±0.6 <sup>a</sup>	10.4±0.8 <sup>b</sup>	16.6±0.9 <sup>f</sup>	2.7±0.3 <sup>b</sup>	310.6±17.3 <sup>b</sup>
	5–20	63.5±5.2 <sup>d</sup>	32.8±2.7 <sup>b</sup>	30.8±2.8 <sup>c</sup>	3.6±0.6 <sup>c</sup>	0.6±0.2 <sup>c</sup>	3.0±0.5 <sup>b</sup>	2.2±0.3 <sup>b</sup>	5.0±0.3 <sup>c</sup>	9.6±0.9 <sup>d</sup>	1.7±0.2 <sup>c</sup>	223.2±23.2 <sup>c</sup>
Savanna	0–5	244.4±23.3 <sup>a</sup>	72.3±18.3 <sup>a</sup>	172.1±21.2 <sup>a</sup>	6.7±1.3 <sup>a</sup>	2.5±0.5 <sup>a</sup>	4.3±1.4 <sup>a</sup>	6.6±1.1 <sup>a</sup>	14.5±1.3 <sup>a</sup>	48.5±4.9 <sup>a</sup>	4.1±0.6 <sup>a</sup>	401.1±45.8 <sup>a</sup>
	5–20	153.5±4.2 <sup>b</sup>	53.9±3.7 <sup>ab</sup>	99.6±7.0 <sup>b</sup>	3.0±0.6 <sup>c</sup>	0.4±0.1 <sup>c</sup>	2.5±0.5 <sup>c</sup>	1.0±0.1 <sup>b</sup>	6.5±0.2 <sup>c</sup>	29.2±2.1 <sup>b</sup>	2.0±0.3 <sup>bc</sup>	220.6±9.7 <sup>c</sup>

Notes: \* TP = total P;  $\text{TP}_i$  = total inorganic P;  $\text{TP}_o$  = total organic P; LP<sub>t</sub> = total labile P; LP<sub>i</sub> = labile inorganic P; LP<sub>o</sub> = labile organic P; Al-P = aluminum bound P; Fe-P = iron bound P; Ca-P = calcium bound P; MBP = microbial biomass P; PA = phosphomonoesterase activities.

**Table 3. The ratio of PA to  $\text{TP}_o$ , and proportions (%) of total phosphorus in different forms**

Site	Depth (cm)	$\text{TP}_o$ :TP	LP <sub>t</sub> :TP	LP <sub>o</sub> :TP	LP <sub>i</sub> :TP	Al-P:TP	Fe-P:TP	Ca-P:TP	PA: $\text{TP}_o$	MBP: $\text{TP}_o$	MBP:TP
Pine plantation	0–5	41.0±2.0 <sup>b</sup>	4.3±0.3 <sup>b</sup>	2.7±0.3 <sup>b</sup>	1.6±0.13 <sup>a</sup>	5.9±0.3 <sup>c</sup>	9.4±0.5 <sup>a</sup>	15.1±0.6 <sup>b</sup>	7.0±0.6 <sup>a</sup>	6.0±0.3 <sup>a</sup>	2.5±0.3 <sup>a</sup>
	5–20	44.3±4.3 <sup>b</sup>	5.4±0.3 <sup>a</sup>	4.5±0.3 <sup>a</sup>	0.9±0.08 <sup>b</sup>	3.2±0.3 <sup>b</sup>	7.5±0.2 <sup>b</sup>	14.4±1.5 <sup>b</sup>	7.9±1.3 <sup>a</sup>	5.8±0.3 <sup>a</sup>	2.5±0.2 <sup>a</sup>
Savanna	0–5	70.7±7.4 <sup>a</sup>	2.8±0.3 <sup>c</sup>	1.8±0.2 <sup>c</sup>	1.0±0.15 <sup>b</sup>	2.8±0.6 <sup>b</sup>	6.2±0.8 <sup>b</sup>	19.9±1.2 <sup>a</sup>	2.4±0.2 <sup>b</sup>	2.5±0.5 <sup>b</sup>	1.7±0.1 <sup>b</sup>
	5–20	64.6±7.1 <sup>a</sup>	1.9±0.2 <sup>d</sup>	1.7±0.1 <sup>c</sup>	0.3±0.04 <sup>c</sup>	0.6±0.05 <sup>a</sup>	4.2±0.1 <sup>c</sup>	18.9±0.9 <sup>a</sup>	2.2±0.1 <sup>b</sup>	1.9±0.2 <sup>c</sup>	1.3±0.1 <sup>b</sup>

### Labile P

Concentrations of LP<sub>t</sub>, LP<sub>i</sub> and LP<sub>o</sub> significantly decreased with vegetation change from savanna to pine plantation in surface soils, not in subsoils, and decreased with soil depth at both sites except that LP<sub>o</sub> under pine plantation was constant with soil depth (Table 2). LP<sub>i</sub> concentration in surface soils was 6 and 3 times of that in subsoils under savanna and pine plantation, respectively. Differences between soil horizons in LP<sub>t</sub> and LP<sub>o</sub> were smaller than that in LP<sub>i</sub>.

LP<sub>o</sub> was the dominant form of labile P at both sites and comprised about 63% and 84% of LP<sub>t</sub> in surface soils and subsoils, respectively. The ratio of LP<sub>o</sub> to LP<sub>t</sub> did not change with vegetation conversion in both soil horizons. Vegetation type and soil depth significantly influenced the proportion of total P in labile form. Contrary to their absolute concentrations, proportions of soil LP<sub>t</sub>, LP<sub>o</sub> and LP<sub>i</sub> in TP under savanna were significantly lower than those under pine plantation in both soil horizons. Change patterns of the ratios of LP<sub>t</sub> to TP and LP<sub>o</sub> to TP with soil depth were opposite between two sites, they increased with soil depth under pine plantation while decreased with soil depth under savanna. The ratio of LP<sub>i</sub> to TP significantly decreased with soil depth at both sites (Table 3).

### Inorganic P fractions

Concentrations of Al-P, Fe-P and Ca-P greatly decreased with soil depth at both sites (Table 2). Vegetation type significantly influenced Fe-P and Ca-P but not Al-P in surface soils. Soil Fe-P concentration under pine plantation was significantly lower than

that under savanna in surface soils but not in subsoils, while Ca-P in both soil horizons under pine plantation was strikingly lower than that under savanna. Intensities of effects of vegetation type on soil inorganic P fractions were in the order: Ca-P > Fe-P > Al-P. Absolute concentrations of these P fractions and the proportions of them in TP significantly decreased in the same order. Effects of soil depth and vegetation type on the proportions of inorganic P fractions in TP differed from the effects on their absolute concentrations (Table 3). Compared with savanna, the plantation had significantly higher ratios of Al-P to TP and Fe-P to TP but lower ratio of Ca-P to TP. The ratios of Al-P to TP and Fe-P to TP decreased obviously with soil depth, whereas ratio of Ca-P to TP was constant.

### Microbial biomass P and phosphomonoesterase activities

MBP concentrations and phosphomonoesterase activities in surface soils were significantly higher than those in subsoils at both sites (Table 2). MBP concentration and phosphomonoesterase activities were affected by vegetation type only in surface soils and their values were significantly higher under savanna than those under pine plantation. However, the ratio of phosphomonoesterase activities to  $\text{TP}_o$  was greatly higher under pine plantation in both soil horizons (Table 3). Differences in MBP and phosphomonoesterase activities between soil horizons were significantly greater under savanna than under pine plantation.

MBP concentrations were similar to corresponding LP<sub>o</sub> concentrations. Mean MBP concentrations across two horizons were

less than 6.0% of  $TP_o$  and 2.5% of TP under Mongolian pine plantation, 2.5% of  $TP_o$  and 1.7% of TP under savanna (Table 3). Though the surface soils under Mongolian pine plantation had lower absolute concentration of MBP compared with adjacent savanna, ratios of MBP to  $TP_o$  and MBP to TP under pine plantation were significantly higher than those under savanna and were not influenced by soil depth.

## Discussion

### P deficiency and the importance of P mineralization

Soil total P level represents the long-term potential of soil P supply, while labile P (bicarbonate extractable P) represents the short-term bioavailability of soil P. Soil labile P consists of phosphate ions in soil solution, inorganic P adsorbed to the surface of soil mineral, and readily mineralized organic P (Cross *et al.* 1995). Concentrations of total P and labile P in this study were very low (Tables 2 and 3) when compared with results from studies on other unfertilized ecosystems around the world (e.g., Oberson *et al.* 1999; Chen *et al.* 2000; Chen 2003). Concentration of TP ranged between  $67.5 \mu\text{g}\cdot\text{g}^{-1}$  and  $244.4 \mu\text{g}\cdot\text{g}^{-1}$ , of which bicarbonate extracted  $LP_i$ ,  $LP_o$ , and  $TP_o$  was only 0.3%–1.6%, 1.7%–4.5%, 41.0%–70.4%, respectively. These results can be attributed to natures of the soil, vegetation and climate in this area. The soil at the study sites is weakly developed sandy soil with neutral pH, low contents of Al oxides, and low cation exchange capacity and P sorption capacity (Leinweber *et al.* 1999). Therefore, pedogenesis resulted in soil infertility and the dominance of acid extractable Ca-P in inorganic P in the soil (Table 3). Additionally, cool arid climate limited microbial activity, and then led to low rate of P mineralization. Therefore, organic P accumulated in the soil and was the major form of soil P under savanna.

As an important component of soil organic matter, soil organic P plays an important role as a source and sink of biologically available P, especially in forest soils (McGill *et al.* 1981). In this P deficient soil with neutral pH and weak biogeochemical process, mineralization of organic P was the main source of plant available P despite of its low rate. Additionally, microbes played crucial role in the biological cycle of soil P, although the ratio of MBP to TP was less than 2.5%.

### Stratification of soil transformation

Concentrations of all soil P fractions and phosphomonoesterase activities were greater in surface soils than those in subsoils, which is consistent with other studies (Lajtha *et al.* 1988; Walbridge *et al.* 1991). The results indicated that surface layer of mineral soil, the interface of floor material and mineral soil, was the most active layer of soil P transformations. Usually, litterfall, the main approach that plants return nutrient back to the soil, is the main supply of soil nutrients, especially for tightly conserved P (Campo *et al.* 2001). Phosphorus recycled through above-ground litterfall and through turnover of fine roots and microbes in surface soils were the most important supply of soil P at both sites. In the savanna, most of fine roots of grasses existed in surface soils. In the Mongolian pine plantation, understory vegetation fully covered the soil surface like in the savanna, and pine tree roots were sparse and mainly distributed in soil depth of 5–20 cm. Therefore, nutrient recycled in subsoils was much less than that in surface soils. The protection of litterfall and forest floor material is essential for sustaining the soil P supplying abil-

ity and ecosystem stability at the study sites.

### The mobility of soil organic P under Mongolian pine plantations

Phosphate ions released from phosphate minerals in surface soils are difficult to move downwards, due to the biogeochemical retention. Because of the low retention of the hydrophilic fraction of dissolved organic matter in mineral soils, particularly in weakly developed soils, organic P is more mobile than inorganic phosphate. Organic P can contribute to 95% of total P leached into deeper soils (Kaiser *et al.* 2003). Labile organic P, mainly phosphate monoesters bound to the mobile polysaccharides, which can be hydrolyzed by phosphatase enzymes, usually does not change with soil depth in forests (Kaiser 2001). That is true in studied Mongolian pine plantation. But in savanna dense root mats retained most of the labile P, so  $LP_o$  decreased significantly with soil depth (Tables 2 and 3). Meanwhile, vertical movement of  $LP_o$  through the soil profile under Mongolian pine plantation led to increases in the ratios of  $LP_o$  to TP and  $LP_i$  to TP with soil depth while all soil P fractions decreased with soil depth (Table 3). Thus,  $LP_o$  was more important in subsoils than that in surface soils. Additionally, the concentration of  $LP_o$  was much greater than that of  $LP_i$  at both sites. Therefore,  $LP_o$  can be an important source of bioavailable P at both sites, especially in Mongolian pine plantation.

### Effects of land-use conversion on soil P status

Due to the nutrient demand and used pattern are strongly affected by vegetation type (e.g., Hooper *et al.* 1998; Chen *et al.* 2000), soil P concentration, bioavailability and distribution have changed greatly after three decades of Mongolian pine afforestation in the study region.

Concentrations of soil TP and all P fractions and phosphomonoesterase activities in surface soils under savanna were significantly higher than those under pine plantation except Al-P (Table 2). Furthermore, our previous study (Zhao *et al.* 2004) showed that soil TP concentration under undisturbed Mongolian pine plantations decreased with stand age. This is because evergreen pine trees take up more nutrients than grasses, and then accumulated them in huge aboveground biomass (Chen *et al.* 2003). Additionally, litterfall in the Mongolian pine plantation returns nutrients back to mineral soil more slowly than that in savanna. Our unpublished data showed that amount of ground litter in spring was much less in savanna ( $166.6 \text{ g}\cdot\text{m}^{-2}$ ) than that in pine plantation ( $663.1 \text{ g}\cdot\text{m}^{-2}$ ), while ground litter in autumn in savanna ( $374.1 \text{ g}\cdot\text{m}^{-2}$ ) was greater than that in pine plantation ( $113.0 \text{ g}\cdot\text{m}^{-2}$ ). Accumulation of partially decomposed plant residues under pine plantation reflected the lower rate of litter decomposition. Higher uptake and lower recycle rate will make Mongolian pine plantation deplete soil P reserve ultimately. These results indicated that in the study region savanna is a better alternation if the sustainable development of ecosystems is taken into account. Large-scale pine afforestation on the semi-arid sandy soils is not advisable and exists in a potential risk.

Although absolute concentrations of TP and most P fractions and PA were significantly lower under pine plantation than those under savanna (Table 2), obviously higher ratio of  $LP_i$  to TP under pine plantation (Table 3) indicated that pine plantation could boost the bioavailability of both soil inorganic and organic P together with the reduction of soil P pool, especially in soils at

5–20 cm.

Contrary to ratios of Al-P to TP and Fe-P to TP, the ratio of Ca-P to TP was obviously higher under savanna than that under the plantation, and it had no significant difference between soil horizons at both sites (Table 3). This showed that soil acidification increased the solubility of Ca-P. Soil pH under pine plantation was significantly lower than that under savanna (Table 1), and our unpublished data indicated that soil pH in rhizosphere soil was obviously lower than that in bulk soil under Mongolian pine plantations. Decreased soil pH accelerated the shift of primary Ca-P to secondary Al-P and Fe-P. Additionally, water soluble inorganic P concentration is below detection in our study. Thus, we conclude that Ca-P was the major inorganic source of available P to Mongolian pine, while LPi consisted of easily soluble Al-P and Fe-P.

Conversion of savanna to pine plantation sharply decreased TP<sub>o</sub> concentration and the ratio of TP<sub>o</sub> to TP, indicating that Mongolian pine afforestation greatly promoted P mineralization. This result is consistent with similar studies on grassland afforestation (Condon *et al.* 1996; Chen *et al.* 2003). Mineralization of soil organic P is highly microbial mediated. Therefore, though absolute values of microbial biomass P and PA under pine plantation were significantly lower than those under savanna, their relative values to TP<sub>o</sub> were greatly higher under pine plantation (Table 3).

Land-use change also affected the distribution of P within soil profile by changing soil P retention processes and use pattern. Compared with the soil under savanna, soil PA and most of P fractions (especially LP<sub>o</sub>) under pine plantation were less variable along soil profile. Above results can be ascribed to the difference in vertical distribution of roots between pine trees and grasses in the savanna. Pine tree roots present deeper in the soil than grasses, so trees in the plantation can utilize soil nutrient in deeper soil layers where roots of grasses in savanna can't reach. So root activities of the pine tree promoted the biogeochemical process in subsoils, whereas, roots in surface soils under savanna retained most of available P and prevented leaching of P to deeper soils.

## Conclusions

Characteristics of P status in this study can be concluded as follows: (1) Soil P pool and P availability were very low. Soil P was mainly in organic form, and microbial activities play essential role in the biological cycle of soil P; (2) Phosphorus transformations mainly occurred in surface soils and the protection of forest floor is essential to maintain soil P pool; (3) Under Mongolian pine plantations, organic P and Ca-P are the main sources of bioavailable P, whereas secondary Al-P and (or) Fe-P are main sinks of bioavailable P; (4) Mongolian pine afforestation on native savanna greatly promoted the mineralization of organic P and slightly increased the release of Ca-P, thus increased soil P bioavailability, but simultaneously sharply reduced total P pool. Savanna is a more sustainable community than Mongolian pine plantation if no artificial P is added. For maintaining the long-term functioning of pine plantation, P fertilization is necessary.

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